Preprint submitted to
Acta Phys. Hung. A 22/1 (2005) 000–000

HEAVY ION PHYSICS

Can we distinguish energy loss from hadron absoprtion?[†]

Alberto Accardi[1]

[1] Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011-3160, U.S.A.

[†] Write-up of poster presented at “Quark Matter 2005”, Budapest, August 2005

Received 30 October 2005

Abstract. Knowing whether a hadron is formed inside or outside the nuclear medium is very important for correctly interpreting jet quenching in heavy-ion collisions. The cleanest experimental environment to study the space-time evolution of hadronization is semi-inclusive DIS on nuclear targets. 2 frameworks are presently competing to explain the observed attenuation of hadron production: quark energy loss, with hadron formation outside the nucleus [2, 3], and nuclear absorption with hadronization starting inside the nucleus [4–6]. I demonstrate that the observed approximate $A^{2/3}$ scaling of experimental data cannot conclusively establish the correctness of either energy loss or absorption.

Keywords: Energy loss, hadron absorption, jet quenching
PACS: 25.30.-c, 25.75.-q, 24.85.+p, 13.87.Fh

In Deep Inelastic Scattering on nuclear targets (nDIS) one observes a suppression of hadron production [1] analogous to hadron quenching in heavy-ion collisions. However, nDIS offers a much cleaner experimental environment to study quark fragmentation: the nuclear medium is well known and the multiplicity in the final state is low. Knowing how the struck quark propagates in cold nuclear matter – most importantly, whether its color is neutralized inside or outside it – is a necessary prerequisite for correctly using hadron quenching data to extract the unknown properties of the hot and dense medium produced at RHIC. Experimental data on hadron production in nDIS are usually presented in terms of the “attenuation ratio” $R_M^h(z) = \frac{1}{N_A^{DIS}}\frac{dN_A^h(z)}{dz} / \frac{1}{N_D^{DIS}}\frac{dN_D^h(z)}{dz}$, i.e., the single hadron multiplicity on a target of mass number A normalized to the multiplicity on a deuterium target. I will only analyze the dependence of R_M^h on the hadron's fractional energy $z = E^h/\nu$, but data also exist binned in the virtual photon energy ν or its virtuality Q^2.

In the hadron absorption model of Ref. [4] hadronization is assumed to happen in 2 stages: (i) the struck quark neutralizes its color and forms a so-called “prehadron”

h^*, and (ii) the observed hadron h is formed. The average formation length of the prehadron, $\langle l^* \rangle(z,\nu)$, and of the hadron, $\langle l^h \rangle(z,\nu)$, are computed in the framework of the standard Lund model. In the HERMES kinematics [1] the prehadron is formed well inside the nucleus while the hadron is produced mostly outside. After its formation, the prehadron can interact with the surrounding nucleons with a cross section $\sigma^*(\nu) = 2/3\,\sigma^h(\nu)$ proportional to the experimental hadron-nucleon cross section σ^h. The proportionality factor is fitted to π^+ production data on a Kr target at $E_{\rm beam} = 27$ GeV^2 [1]. The probability $S^A_{f,h}(z,\nu)$ that neither the prehadron nor the hadron interact can be computed using transport differential equations [4]:

$$S^A_{f,h}(z,\nu) = \int d^2b\, dy\, \rho_A(b,y) \times \int_y^\infty dx' \int_y^{x'} dx\, \frac{e^{-\frac{x-y}{\langle l^* \rangle}}}{\langle l^* \rangle} e^{-\sigma_* \int_x^{x'} ds A \rho_A(b,s)} \frac{e^{-\frac{x'-x}{\langle \Delta l \rangle}}}{\langle \Delta l \rangle} e^{-\sigma_h \int_{x'}^{\infty} ds A \rho_A(b,s)} \qquad (1)$$

where $\Delta l = l^h - l^*$, and ρ_A is the nuclear density. One can recognize exponential probability distributions for prehadron and hadron formation. Note also the integration over the interaction points (b,y) of the virtual photon γ^* with the quark. The hadron multiplicity is computed, at leading order in pQCD, as follows:

$$\frac{1}{N_A^{DIS}} \frac{dN_A^h(z)}{dz} = \frac{1}{\sigma^{lA}} \int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2 q_f(x,Q^2) \frac{d\sigma^{lq}}{dx d\nu} S^A_{f,h}(z,\nu) D_f^h(z,Q^2)\ . \qquad (2)$$

Here σ^{lq} and σ^{lA} are the lepton-quark and lepton-nucleus cross sections. q_f is the f-quark distribution function, and D_f^h its fragmentation function. The model neglects hadron elastic scatterings, diffractive hadron production, and resonance production and decay. Therefore it is applicable at $0.4 \lesssim z \lesssim 0.9$.

Energy loss models [2, 3] assume that the struck quark hadronizes well outside the medium, and that hadron attenuation is due to medium-induced gluon radiation off the quark. The quark's energy is reduced from $E_q = \nu$ to $E_q = \nu - \epsilon$, where ϵ is the total energy of the radiated gluons, which translates into a modified fragmentation function:

$$\tilde{D}_f^h(z,Q^2;L) = \int_0^{(1-z)} d\Delta z\, \mathcal{P}(\Delta z\,;\hat{q},L) \frac{1}{1-\Delta z} D_f^h(\frac{z}{1-\Delta z},Q^2) + p_0(\hat{q},L)\, D_f^h(z,Q^2)\ .$$

The "quenching weight" $\mathcal{P}(\Delta z)$ is the probability distribution of a fractional energy loss $\Delta z = \varepsilon/\nu$, and p_0 is the probability of zero energy loss [7]. The quenching weight depends on the quark's in-medium path length $L_A(b,y)$ and on the transport coefficient $\hat{q}(b,y)$, defined to take into account non-uniform nuclear density [8]. $\hat{q}(0,0) = 0.5$ GeV^2/fm, is fitted to π^+ production on a Kr target analogously to the absorption model. Hadron multiplicity is then computed as in Eq. (2), using the modified $\tilde{D}$ and $S^A = 1$. Finally, an integration over (b,y) is performed.

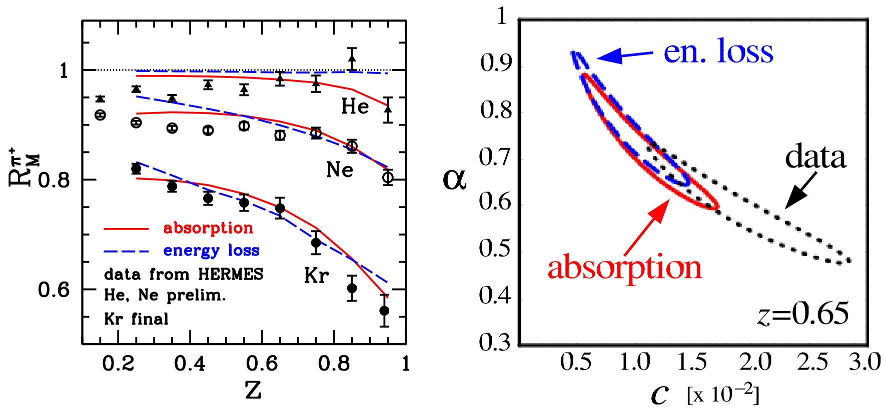

Fig. 1. Left: π^+ multiplicity ratio in the absorption and energy loss models compared to HERMES data at a beam energy of 27 GeV^2 [1]. Right: results of the $R_M = cA^\alpha$ fit for {He,N,Ne,Kr} at z=0.65 (solid: absorption; dashed: energy loss; dotted: data [1]). More z-bins and case studies can be found in [8].

In Fig. 1, the 2 models are compared to HERMES data. Both describe well the data, and look similar despite the different physics processes. Quite surprisingly, this similarity holds up to very heavy targets like Pb.

A naïve argument, often repeated in discussions and seminars on heavy-ion collisions, is that in first approximation $1 - R_M^h \propto A^{2/3}$ in energy loss models because the average energy loss $\langle \epsilon \rangle \propto \langle L_A^2 \rangle \propto A^{2/3}$. On the other hand, in absorption models the survival probability is proportional to the amount of traversed matter, so that $1 - R_M^h \propto \langle L_A \rangle \propto A^{1/3}$. Therefore, it is concluded, a simple analysis of the A-dependence of R_M^h (or of R_{AA}^h in heavy-ion collisions) will clearly signal which one of the 2 models is correct.

The above argument is wrong! Where the argument actually fails is for absorption models [9]. If the prehadron were produced always at the γ^*-quark interaction point (i.e., $\langle l^* \rangle = 0$) then $R_M = c\,A^{1/3}$ at all orders in $A^{1/3}$. However, if we allow for a nonzero $\langle l^* \rangle$, its dimensions must be neutralized by the nuclear radius R_A, introducing extra powers of $A^{1/3}$. Quite generally, if the probability distribution for the prehadron formation length is finite at zero formation length, then $R_M^h \propto A^{2/3} + O(A)$, the same power found in energy loss models [4]. This is the case for the presented model, as well as for most other absorption models.

Then, we can hope to distinguish energy loss from hadron absorption by studying the *breaking* of the $A^{2/3}$ law. To this purpose, it was proposed in [4] to select a set of targets $\{A_1, A_2, \ldots, A_n\}$, fix the z bin, and perform a fit of the form $1 - R_M^h(z) = c(z)A^{\alpha(z)}$. Both c and α must be considered fit parameters for 2 reasons: first, both contain information on the dynamics of the hadronization process [4, 8]; second, one can always redefine c in order to absorb a part of α biasing the result, so that it is more correct to ask the fit itself what are the correct values of

the 2 parameters. The results of the fit are presented in terms of 2σ confidence contours in the (c, α) plane, see Fig. 1. This analysis is powerful: it is sensitive to model parameters like $\hat{q}$ [8], and to different physical mechanisms: e.g., partial quark deconfinement in nuclei [4]. However, when we apply the fit to the 2 models described in the previous section, we have a surprise: energy loss and absorption are indistinguishable. The same holds true for all z bins. Increasing the number of targets and the span in atomic number does not help in separating the 2 models, either, but clearly shows a non negligible breaking of the $A^{2/3}$ law at $A \gtrsim 80$ [8].

In summary, single hadron suppression obeys a $A^{2/3}$ law (broken at $A \gtrsim 80$) in both energy loss and absorption models. Thus, the observed approximate $A^{2/3}$ scaling of experimental data for light nuclei cannot be used as a proof of the energy loss mechanism, as is often done. Even the more refined analysis in terms of (c, α) fits cannot clearly distinguish the 2 classes of models, though it will help in checking the details of the "correct" model after this is established by other means. To answer the very important question of whether or not the struck quark starts hadronizing inside the nucleus, we need to consider more exclusive observable, like the z-dependence of hadron's p_T-broadening and Cronin effect [5] or dihadron correlations [10].

Acknowledgments

A special thank to D.Grünewald for his help in the initial phase of this investigation. This work is partially funded by the US Department of Energy grant DE-FG02-87ER40371.

References

1. A. Airapetian *et al.* [HERMES], *Phys. Lett. B* **577** (2003) 37; G. Elbakian *et al* [HERMES], Proceedings "DIS 2003", St.Petersburg, April 23-27, 2003; V.T. Kim and L.N. Lipatov eds., page 597.
2. E. Wang and X. N. Wang, *Phys. Rev. Lett.* **89** (2002) 162301.
3. F. Arleo, *Eur. Phys. J. C* **30** (2003) 213 and *JHEP* **0211** (2002) 044.
4. A. Accardi *et al. Nucl.Phys.A* in press [arXiv:hep-ph/0502072].
5. B. Z. Kopeliovich *et al. Nucl. Phys. A* **740** (2004) 211.
6. T. Falter *et al. Phys. Rev. C* **70** (2004) 054609.
7. C. A. Salgado and U. A. Wiedemann, *Phys. Rev. D* **68** (2003) 014008.
8. A. Accardi, poster at "Quark Matter 2005", Budapest, Aug 2005; talk at "Parton propagation through QCD matter", ECT*, Trento (ITA), Sep-Oct 2005 [http://nt3.phys.columbia.edu/people/aaccardi/transparencies/]
9. In energy loss models, a leading order $A^{2/3}$ term can be obtained only by neglecting finite-medium corrections and energy conservation, $\Delta z < (1 - z)$. Nonetheless, for light nuclei up to Kr the 2/3 power is approximately correct.
10. A. Airapetian *et al.* [HERMES], arXiv:hep-ex/0510030.